Optimization of the coupled grid connection of offshore wind farms

Dirk Schoenmakers

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Content

- Problem description + research question
- Model description
- Grid connection technologies
- Technical model
- Economical model
- Application of model: case study + scenarios
- Results and conclusions
Problem description

- Many offshore wind farms under development
- Increasing distance and rated power wind farms
- Relative distance between wind farms decreases
- Goal: decrease costs

Question rises:

*How can the grid connection of multiple offshore wind farms of different power ratings and distances to shore be optimized on basis of economical and technical criteria?*
Model description

- Optimization of:
  - Investment costs
  - Losses in the system

\[ \text{Optimized system} \]
Model description – investment costs

- Investment cost components:
  - Offshore High Voltage Station (OHVS)
  - Interconnection cables (offshore)
  - Main OHVS or converter station
  - Grid connection cables (offshore & onshore)
  - Onshore substation or converter station
  - Reactive power compensation (for AC systems)
Model description – losses

Offshore substations

Power production wind farms

Main offshore substation or converter station

Offshore reactive compensation

Submarine cables

Land cables

Onshore substation or converter station

Onshore reactive compensation

Power fed into onshore grid

Wind farm power production

Availability

Wake loss

Infield loss

Loss offshore substation

Loss main offshore substation or converter station

Loss land cables

Loss connection cables between offshore wind farms

Loss submarine cables

Loss onshore substation or converter station

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# Grid connection technologies

<table>
<thead>
<tr>
<th></th>
<th>HVAC</th>
<th>HVDC VSC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage levels</td>
<td>132 kV, 150 kV, 220 kV</td>
<td>±150 kV, ±300 kV</td>
</tr>
<tr>
<td>Maximum transmission capacity per cable system</td>
<td>190 MW at 132 kV, 215 MW at 150 kV, 310 MW at 220 kV</td>
<td>740 MW at ±150 kV, 1480 MW at ±300 kV</td>
</tr>
<tr>
<td>Type of cable used</td>
<td>XLPE</td>
<td>XLPE</td>
</tr>
<tr>
<td></td>
<td>Three phase offshore</td>
<td>Single phase both offshore and onshore in bipolar systems</td>
</tr>
<tr>
<td></td>
<td>Single phase onshore</td>
<td></td>
</tr>
<tr>
<td>Transmission capacity distance depending</td>
<td>Yes, reactive power compensation required</td>
<td>No</td>
</tr>
<tr>
<td>Offshore substations in operation</td>
<td>Yes, many</td>
<td>Yes, only 1</td>
</tr>
<tr>
<td>Space requirement offshore substation</td>
<td>Small, Relative volume 1</td>
<td>Large, Relative volume 2.5 - 3</td>
</tr>
</tbody>
</table>
Content

- Problem description + research question
- Model description
- Grid connection technologies
- **Technical model**
- Economical model
- Application of model: case study + scenarios
- Results and conclusions
Infield Cable Loss – Transformer Loss – Cable Loss – Reactive Power Loss – Converter Loss

Technical model – Power production

● Power production:
  - Power curve turbine + wind speed distribution (Weibull)
  - Availability (avg 92% offshore)
  - Wake loss (avg 10% offshore)

● Infield cable loss:
  - Multiple conductor cross sections
  - Aluminum and copper conductors
  - Current depending
  - % at rated current, typically ~0.5% - 1.0%

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Technical model – Loss transformer

- Losses transformer:
  - No load losses:
    - magnetizing core
    - constant, typically ~0.046%
  - Full load losses:
    - Losses in windings
    - current depending, typically ~0.26%

\[ P_{\text{loss no load}} + \left( \frac{I(V)}{I_{\text{rated}}} \right)^2 \cdot P_{\text{loss full load}} \]
Technical model – Cable model

- Electrical behavior:
  - Ohmic losses (temperature dependant)
  - Dielectric losses (losses in insulation material)
  - Induced losses (due to induced currents in metallic sheaths and armoring of cable)
Technical model – Cable model

- Cable losses:
  - Ohmic losses:
    - Temperature dependent resistance:
    - Increased effective resistance due to induced currents (only for AC):
      \[ R_\theta = R_{20} (1 + a_\theta(\theta - 20))(1 + \lambda_1 + \lambda_2) \]
  - Dielectric losses (only for AC):
    - Losses due to charging current: \[ W_d = n I_{\text{charge}} \frac{V_L}{\sqrt{3}} \tan(\delta) \]
    - \[ I_{\text{charge}} = 2\pi f C'L \frac{V_L}{\sqrt{3}} \]
Technical model – Cable model

- Electrical behavior under AC:
  - Effect of charging current:
    - Current distribution along cable: \( I_{\text{cable}}(x) = \sqrt{I_{\text{charge}}^2(x) + I_{\text{windfarm}}^2} \)

**Infield Cable Loss – Transformer Loss – Cable Loss – Reactive Power Loss – Converter Loss**

**Current Distribution Along a Cable**

- \( I_{\text{max}} \)
- \( P = 210 \text{ MW} \)
- \( P = 150 \text{ MW} \)
- \( P = 75 \text{ MW} \)
- \( P = 10 \text{ MW} \)

150 kV
3-phase cable
800 mm\(^2\) conductors

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Technical model – Cable model

- Electrical behavior under AC:
  - Effect of charging current:
    - Maximum cable rating →
  Max. power transmission vs. distance

\[ I_{\text{max,WF}} = \sqrt{I_{\text{rated}}^2 - I_{\text{charge,total}}^2} \]
Technical model – Cable model

- Thermal behavior:

Influence up to 70%!
Technical model – Cable model

- Thermal behavior:
  - Rated current dependent on operational conditions → External thermal resistance soil

- Current rating for different soil temperatures

- Typical offshore
- Typical onshore
Technical model – Reactive compensation

- Type of reactive compensation:
  - Dependant on requirements at grid connection point
  - Shunt reactor assumed

\[ Q = n \frac{V_L}{\sqrt{3}} I_{charge} \]

\[ \eta \approx 0.15\% \]
Technical model – HVDC VSC converter
Infield Cable Loss – Transformer Loss – Cable Loss – Reactive Power Loss – Converter Loss

Technical model – HVDC VSC converter

- Loss model based on published losses Murraylink (220 MW) and Cross Sound Cable (330 MW) [both operational since 2002]
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Economical model

- Modeling of losses: 100 €/MWh
- Modeling of investment costs:
  - Cables (submarine and land)
  - Cable installation (offshore and onshore)
  - Offshore substation (AC – OHVS)
  - Onshore substation (AC)
  - Offshore converter station
  - Onshore converter station
- Economical model based on:
  - Literature
  - Data known within Evelop
Economical model

- Costs AC substation:
  - Offshore: 130 k€/MVA
  - Onshore:
    - Transformer: 25 k€/MVA
    - Connection to grid (circuit breakers/switches/...): 1000 k€/bay

- Costs reactive compensation (shunt reactor):
  - Offshore: 35 k€/MVAr
  - Onshore: 25 k€/MVAr
Economical model

- Costs HVDC VSC converter stations:
  - Offshore:
    - ±150 kV: 200 k€/MW
    - ±300 kV: 220 k€/MW
  - Onshore:
    - ±150 kV: 85 k€/MW
    - ±300 kV: 92.5 k€/MW
Economical model

- Costs cable installation:
  - Offshore:
    - 1x3-phase AC: 275 k€/km
    - 2x1-phase DC: 250 k€/km
  - Onshore:
    - 3x1-phase AC: 175 k€/km
    - 2x1-phase DC: 150 k€/km
Economical model

- Costs submarine and land cables, depending on:
  - # phases
  - Type conductor (Cu/Alu)
  - Conductor cross section
  - Voltage
  - Metal prices
  - Exchange rates

![Currency Exchange Rate USD vs EURO]

>30% Decrease!
Economical model

- Costs submarine and land cables:

![Graph showing calculated price for 3-phase copper submarine AC cables - 220 kV](image_url)
Economical model - Verification

- Verification based on commercial projects:
  - HVAC
    - Horns Rev: +12.8%
    - Nysted: +10.4%
  - HVDC VSC:
    - Estlink: +5.1%
    - Nord E.ON1: -17.7%

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Supply</td>
<td>Installation</td>
<td>Supply</td>
<td>Installation</td>
<td>Offshore</td>
<td>Substation</td>
</tr>
<tr>
<td>Horns Rev</td>
<td>6.3</td>
<td>6.0</td>
<td>9.9</td>
<td>5.8</td>
<td>20.8</td>
<td>2.0</td>
</tr>
<tr>
<td>Nysted</td>
<td>3.3</td>
<td>3.2</td>
<td>3.1</td>
<td>3.0</td>
<td>23.4</td>
<td>1.0</td>
</tr>
</tbody>
</table>

- 1st offshore converter station
- Long cable trajectory both offshore and onshore
Economical model – Optimization process

- Cost components:
  - Investment costs (year 0)
  - Operational costs (electrical losses, year 0 to year 20)
- Model future operational costs to present value: NPV method

\[ NPV = C_0 + \sum \frac{C_t}{(1+r)^t} \]

- Important variable: interest/depreciation rate ‘r’
- ‘r’ set at 8%
Content

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Application of model

- Case study ‘Trident’ offshore wind farms
- Scenarios:
  - ‘Base case’: individual grid connections
  - ‘Market development’: 2 or 3 wind farms with coupled grid connection
    - WR & SB: ~600 MW
    - WR & K: ~625 MW
    - SB & K: ~660 MW
    - WR & SB & K: ~950 MW
- Comparing all different technologies:
  - 132 kV, 150 kV and 220 kV HVAC
  - ±150 kV and ±300 kV HVDC VSC
1 Wind Farm – 2 Wind Farms – 3 Wind Farms – Sensitivity Analysis

Application of model

Costs Grid Connection 'Scheveningen Buiten'

Type of Grid Connection

- HVAC 132 kV
- HVAC 150 kV
- HVAC 220 kV
- HVDC VSC ±150 kV
- HVDC VSC ±300 kV

Legend:
- OHVS
- Submarine Cables
- Onshore Cable Installation
- Onshore HVDC Converter
- Offshore Reactive Compensation
- Submarine Cable Installation
- Onshore Substation
- Offshore HVDC Converter
- Onshore Reactive Compensation
- Offshore Cables
- Losses

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# Application of model

- Coupled grid connection: 2 wind farms, ±600 MW

## Costs Coupled Grid Connection 'West Rijn' and 'Scheveningen Buiten'

<table>
<thead>
<tr>
<th>Type of Grid Connection</th>
<th>Individual Grid Connection</th>
<th>Coupled Grid Connection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>System</td>
<td>Total Costs [M€]</td>
</tr>
<tr>
<td>'West Rijn'</td>
<td>220 kV HVAC</td>
<td>143.9</td>
</tr>
<tr>
<td>'Scheveningen Buiten'</td>
<td>150 kV HVAC</td>
<td>170.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>-</td>
<td><strong>313.9</strong></td>
</tr>
</tbody>
</table>

- 1.43% lower price
- 9.4% higher losses
**Application of model**

- Coupled grid connection: all 3 wind farms, ±950 MW

### Costs Coupled Grid Connection 'West Rijn', 'Scheveningen Buiten' and 'Katwijk'

<table>
<thead>
<tr>
<th></th>
<th>Individual Grid Connection</th>
<th>Coupled Grid Connection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>System</td>
<td>Total Costs [M€]</td>
</tr>
<tr>
<td>‘West Rijn’</td>
<td>220 kV HVAC</td>
<td>143.9</td>
</tr>
<tr>
<td>‘Scheveningen Buiten’</td>
<td>150 kV HVAC</td>
<td>170.0</td>
</tr>
<tr>
<td>‘Katwijk’</td>
<td>150 kV HVAC</td>
<td>172.7</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>486.6</strong></td>
</tr>
</tbody>
</table>

-~equal price
- 5.0% higher losses
Application of model

- Sensitivity analysis:
  - Cable price: 100% to 130%
  - Price electricity: 100 €/MWh to 140 €/MWh
  - Interest/depreciation rate ‘r’: 8% to 10%
  - Price offshore converter station: down to 175 k€/MW
  - Offshore cable length: 40 km to 100 km
Sensitivity analysis: cable price

- Cable price: 100% to 130%, connection all 3 wind farms

### Sensitivity analysis: cable price increase

<table>
<thead>
<tr>
<th>Technology</th>
<th>Individual Grid Connection</th>
<th>Coupled Grid Connection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total Costs [M€]</td>
<td>20 Year Losses [GWh]</td>
</tr>
<tr>
<td>‘West Rijn’</td>
<td>220 kV HVAC</td>
<td>159.0</td>
</tr>
<tr>
<td>‘Scheveningen Buiten’</td>
<td>150 kV HVAC</td>
<td>187.4</td>
</tr>
<tr>
<td>‘Katwijk’</td>
<td>150 kV HVAC</td>
<td>189.8</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>-</td>
<td><strong>536.2</strong></td>
</tr>
</tbody>
</table>

- **1.49% lower price**
- **6.3% higher losses**
Sensitivity analysis: price electricity

- Price electricity: up to 140 €/MWh, connection all 3 wind farms

### Sensitivity analysis: electricity price increase

<table>
<thead>
<tr>
<th>Technology</th>
<th>Individual Grid Connection</th>
<th>Coupled Grid Connection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>System</td>
<td>Total Costs [ME]</td>
</tr>
<tr>
<td></td>
<td>1 Wind Farm –</td>
<td></td>
</tr>
<tr>
<td>‘West Rijn’</td>
<td>220 kV HVAC</td>
<td>154.1</td>
</tr>
<tr>
<td>‘Scheveningen Buiten’</td>
<td>150 kV HVAC</td>
<td>183.1</td>
</tr>
<tr>
<td>‘Katwijk’</td>
<td>150 kV HVAC</td>
<td>187.3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>524.5</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Technology</th>
<th>Individual Grid Connection</th>
<th>Coupled Grid Connection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>System</td>
<td>Total Costs [ME]</td>
</tr>
<tr>
<td></td>
<td>2 Wind Farms –</td>
<td></td>
</tr>
<tr>
<td></td>
<td>220 kV HVAC</td>
<td>154.1</td>
</tr>
<tr>
<td></td>
<td>±150 kV DC</td>
<td>354.1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>523.9</strong></td>
</tr>
</tbody>
</table>

- **0.11% lower price**
- **5.9% higher losses**
Sensitivity analysis: interest rate ‘r’

- Interest/depreciation rate ‘r’: up to 10%, connection all 3 wind farms

<table>
<thead>
<tr>
<th>Technology</th>
<th>Individual Grid Connection</th>
<th>Coupled Grid Connection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>System</td>
<td>Total Costs [M€]</td>
</tr>
<tr>
<td>‘Scheveningen Buiten’</td>
<td>150 kV HVAC</td>
<td>165.6</td>
</tr>
<tr>
<td>‘Katwijk’</td>
<td>150 kV HVAC</td>
<td>167.8</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>-</strong></td>
<td><strong>333.4</strong></td>
</tr>
</tbody>
</table>

0.90% lower price
3.1% higher losses
Sensitivity analysis: price converter station

- Price offshore converter station:
  - ±150 kV: 175 k€/MW
  - ±300 kV: 192.5 k€/MW

- Connection all 3 wind farms

Results Sensitivity Analysis of Price Offshore Converter of 175 kEURO/MW
Sensitivity analysis: offshore cable length

- Offshore cable length: 40 km to 100 km
- Connection all 3 offshore wind farms

### Results - Sensitivity Analysis: Offshore Grid Connections

#### Optimized Individual Grid Connections

<table>
<thead>
<tr>
<th></th>
<th>40 km</th>
<th>50 km</th>
<th>60 km</th>
<th>70 km</th>
<th>80 km</th>
<th>90 km</th>
<th>100 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>WR</td>
<td>220 kV AC</td>
<td>220 kV AC</td>
<td>132 kV AC</td>
<td>132 kV AC</td>
<td>±150 kV DC</td>
<td>±150 kV DC</td>
<td>±150 kV DC</td>
</tr>
<tr>
<td>SB</td>
<td>150 kV AC</td>
<td>150 kV AC</td>
<td>150 kV AC</td>
<td>150 kV AC</td>
<td>150 kV AC</td>
<td>±300 kV DC</td>
<td>±300 kV DC</td>
</tr>
<tr>
<td>K</td>
<td>150 kV AC</td>
<td>150 kV AC</td>
<td>150 kV AC</td>
<td>150 kV AC</td>
<td>±300 kV DC</td>
<td>±300 kV DC</td>
<td>±300 kV DC</td>
</tr>
</tbody>
</table>

#### Optimized Coupled Grid Connections

<table>
<thead>
<tr>
<th></th>
<th>40 km</th>
<th>50 km</th>
<th>60 km</th>
<th>70 km</th>
<th>80 km</th>
<th>90 km</th>
<th>100 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>WR + SB</td>
<td>220 kV AC</td>
<td>220 kV AC</td>
<td>220 kV AC</td>
<td>220 kV AC</td>
<td>±300 kV DC</td>
<td>±300 kV DC</td>
<td>±300 kV DC</td>
</tr>
<tr>
<td>WR + K</td>
<td>220 kV AC</td>
<td>220 kV AC</td>
<td>220 kV AC</td>
<td>220 kV AC</td>
<td>±300 kV DC</td>
<td>±300 kV DC</td>
<td>±300 kV DC</td>
</tr>
<tr>
<td>SB + K</td>
<td>220 kV AC</td>
<td>220 kV AC</td>
<td>220 kV AC</td>
<td>220 kV AC</td>
<td>±300 kV DC</td>
<td>±300 kV DC</td>
<td>±300 kV DC</td>
</tr>
<tr>
<td>WR + SB + K</td>
<td>220 kV AC</td>
<td>220 kV AC</td>
<td>220 kV AC</td>
<td>220 kV AC</td>
<td>±300 kV DC</td>
<td>±300 kV DC</td>
<td>±300 kV DC</td>
</tr>
</tbody>
</table>

#### Cable Length [km]

- WR & SB: ~600 MW
- WR & K: ~625 MW
- SB & K: ~660 MW
- WR & SB & K: ~950 MW

#### Offshore Grid Connections:

- WR: 284 MW
- SB: 320.4 MW
- K: 342 MW

**Sensitivity Analysis**

- 50 €/MWh
- 'r': 5.5%
Results and Conclusions

- Costs optimized grid connections AC technologies similar, DC much higher (losses + investment)
- In general 220 kV HVAC most optimized solution
- In case of coupled grid connection cost benefit very small (only 1% to 4% lower costs)
- Sensitivity analysis showed no difference in results
- HVDC VSC system economically feasible for cable lengths of 80km to 100km (developer’s point of view)
- For developer economically not feasible to arrange coupled grid connection!